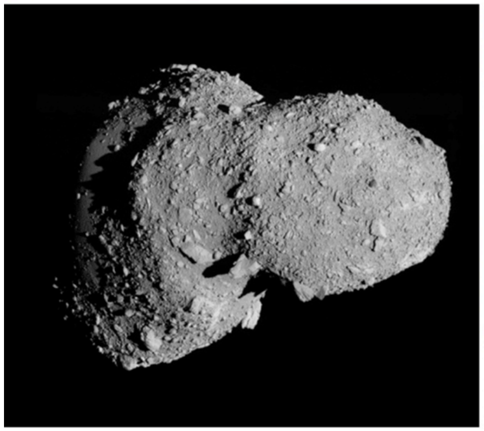
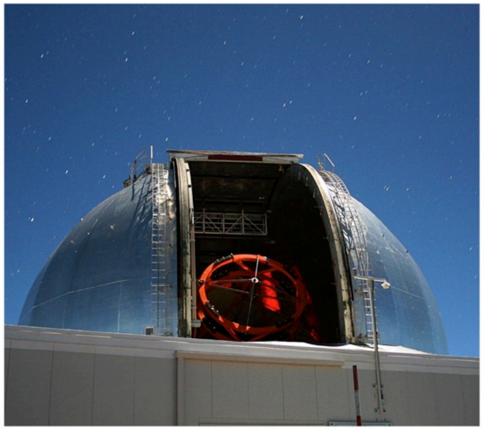
National Aeronautics and Space Administration

Asteroid Redirect Mission Alternate Approach Trade Study

Mission Formulation Review (MFR)

Dan Mazanek, Senior Space Systems Engineer
Langley Research Center (LaRC)





Study Team

Core Team

Name	Role/Expertise	Affiliation
Dan Mazanek	Study Coordinator	LaRC
Gabe Merrill	Study Deputy Coordinator	LaRC
David Reeves	Study Deputy Coordinator	LaRC
Paul Speth	Study Deputy Coordinator	LaRC
Lindley Johnson	HQ SMD Study Executive	HQ
Rob Landis	HQ SMD integration and programmatics	HQ
Tony Colaprete	Planetary science, flight Instrumentation, spectroscopy (UV – NIR), mission development	ARC
John Karcz	Space scientist	ARC
Maria Babula	Space propulsion and mission analysis	GRC
Michael Amato	Planetary and small body robotic mission system engineering and design, robotic mission instrument and sensor capabilities	GSFC
Joe Nuth	Primitive solar system materials, physical properties of asteroids and small bodies, Early solar system processes	GSFC
Paul Abell	Planetary scientist specializing in NEO characterization	JSC
Stan Love	Human space operations (extra-vehicular activity and robotic manipulator operations) and planetary science (asteroid physical properties and collisional evolution)	JSC
Rob Mueller	Granular mechanics, regolith operations and in-situ resources	KSC
Phil Metzger	Granular mechanics, regolith operations and in-situ resources	KSC
Tim Collins	Robotic systems, structural analysis	LaRC
John Dankanich	Mission Design and Trajectory Optimization	MSFC
Randy Hopkins	Mission analysis and trajectory design	MFSC

Additional Contributors

Name	Affiliation
John Dorsey	LaRC
Tony Griffith	JSC
Sharon Jefferies	LaRC
Tom Jones	LaRC
Carlos Roithmayr	LaRC
Geoffrey Statham	MSFC
Corinne Vassallo	MSFC
Dave Cornelius	LaRC, AMA
Kevin Greer	LaRC, AMA
Min Qu	LaRC, AMA
Mark Jesick	LaRC, AMA
Kevin Larman	LaRC, AMA
Josh Sams	LaRC, AMA
Haijun Shen	LaRC, AMA
Hilary Shyface	LaRC, AMA

Acronyms

NASA Ames Research Center	ARC
NASA Glenn Research Center	GRC
NASA Goddard Space Flight Center	GSFC
NASA Headquarters	HQ
NASA Johnson Space Center	JSC
NASA Kennedy Space Center	KSC
NASA Langley Research Center	LaRC
NASA Marshall Space Flight Center	MSFC
Analytical Mechanics Associates, Inc.	AMA

Scope and Description

- Alternate Approach Trade Study (AATS) is an initial, high-level assessment to examine a feasible alternate approach for the robotic segment of the Asteroid Redirect Mission (ARM).

- AATS focused on altering the trajectory of a large Near-Earth Asteroid (NEA) of ~100+ m in diameter and returning a boulder (1-10 m diameter) from the surface to a stable orbit in lunar vicinity, with the following additional objectives:
  - Provide valuable new data on Near-Earth Asteroids (NEAs) of a hazardous size and demonstrate how the threat could be averted.
  - Support various Agency goals by addressing a wider range of robotic and human exploration objectives, provide more relevant operational experience, and effectively facilitate or demonstrate asteroid interaction activities.
  - Allow greater mission flexibility with the opportunity to deploy additional payloads at a large NEA – planetary defense, science, resource utilization, and human exploration.

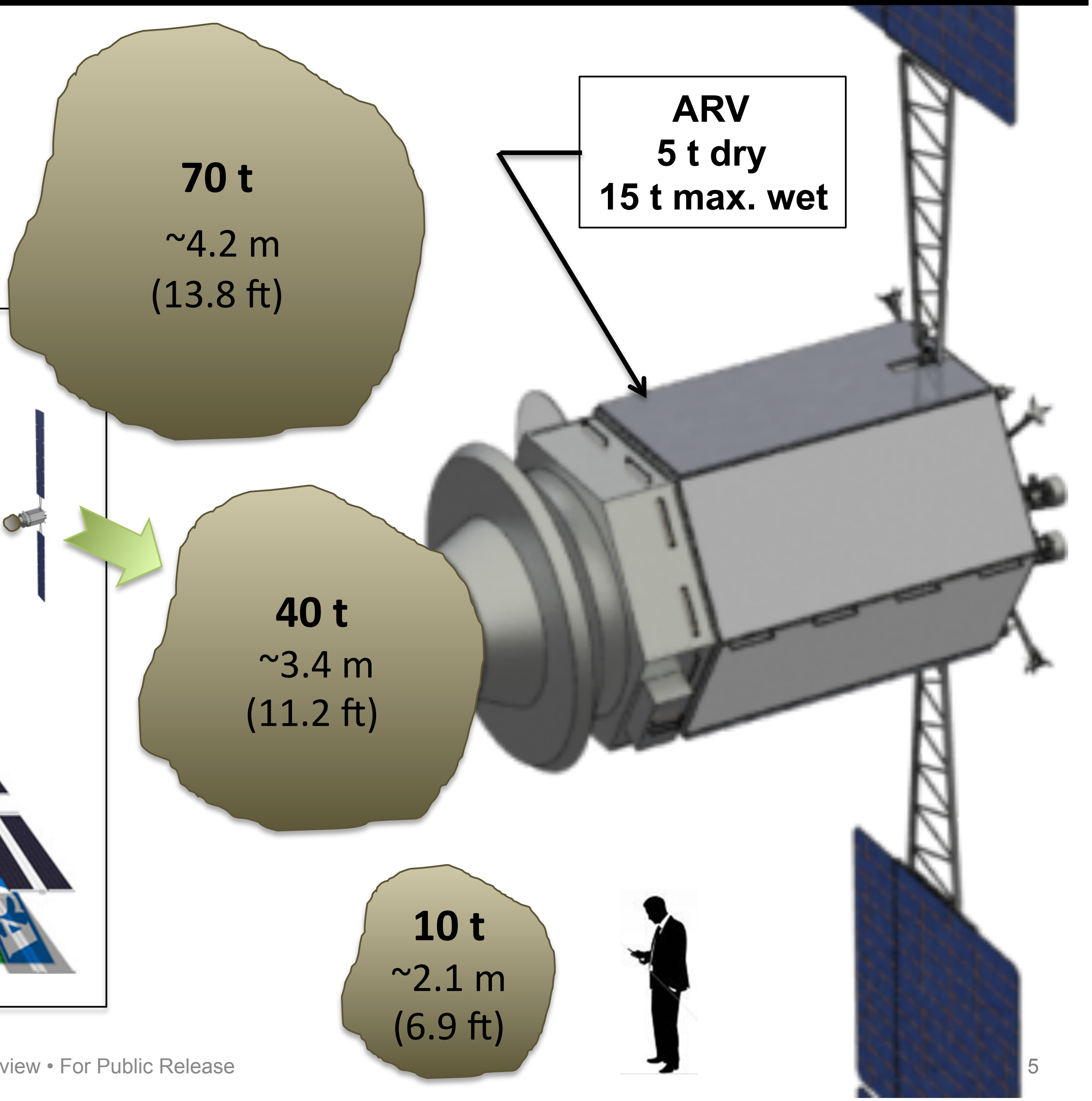
- Multi-center effort for the ARM Mission Formulation Review (MFR) with the potential for more detailed assessment in FY 2014.

Summary of Study Ground Rules & Assumptions

- Launch on or after June 1, 2018.
- Utilize Asteroid Redirect Vehicle (ARV) with Solar Electric Propulsion (SEP) consistent with current reference approach.
  - 4.97 metric ton (t) ARV with maximum of 10 t of xenon propellant.
  - ARV modifications as required to effectively perform alternate mission.
  - Not constrained to the reference ARV capture system.
- Target is a ~100+ m diameter NEA with ~1+ hour rotation period. Target is hazardous size, but not necessarily a Potentially Hazardous Asteroid (PHA).
- Acquire boulder and return it to a Lunar Distant Retrograde Orbit (LDRO) by 2025.
- Demonstrate Planetary Defense (PD) technique(s) on the target NEA.
- Track target NEA with sufficient accuracy to determine PD demo effectiveness.
- Preferred type of target NEA is a water-rich carbonaceous object, however this is a secondary consideration.
- Cost analysis not performed but the objective is to not increase mission cost.

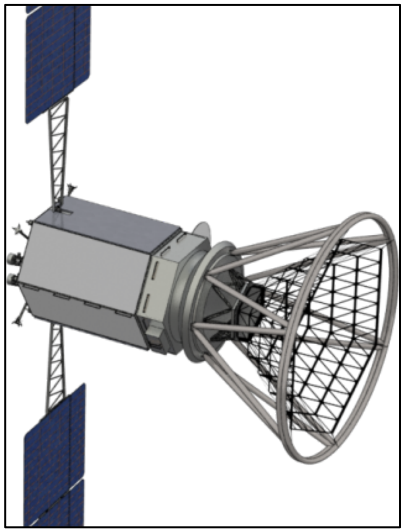
Target NEA & Boulder Size/Mass Comparison

NEA & boulder mass estimates assume density of 2 g/cm^3

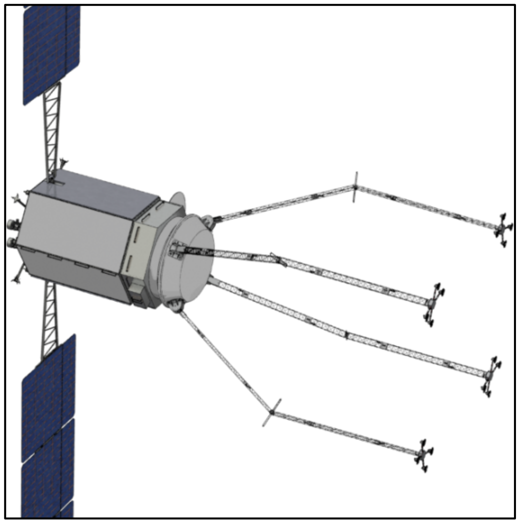


Multiple Options for Boulder Retrieval

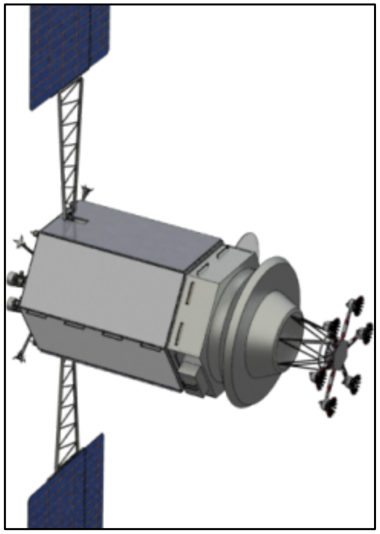
Capture System Option Examples



Net with inflatable/deployable mechanism

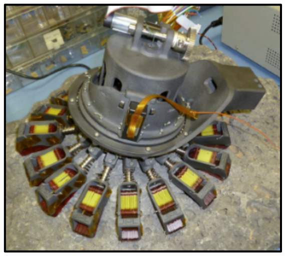


Manipulators with end effectors/grippers

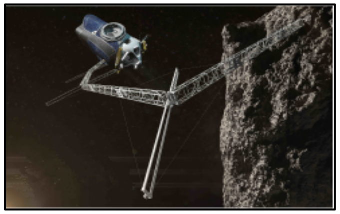


Grippers only

- A variety of capture system options and technologies are applicable for retrieving a coherent/monolithic boulder – optional bag for containment.
- Specialized robotic tools and end effectors can be utilized.
  - Manipulator or spacecraft mounted.
  - Grapple, anchor, push/pull, sample, position, cut, drill, etc.
- In the unlikely event that a suitable boulder or boulders could not be retrieved, a contingency capability to collect regolith can be included (surface contact pads, OSIRIS-REx sample collector, etc.).

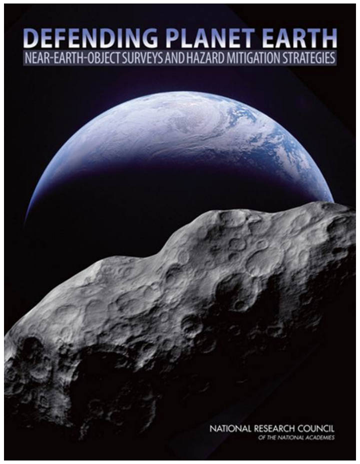


Microspine Technology



Tendon-Actuated Manipulator Technology

Planetary Defense Approach



2010 National Research Council Committee

"Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies"

– **Finding:** **No single approach to mitigation is appropriate and adequate** for completely preventing the effects of the full range of potential impactors, although civil defense is an appropriate component of mitigation in all cases. **With adequate warning, a suite of four types of mitigation is adequate to mitigate the threat from nearly all NEOs except the most energetic ones.**

TABLE 5.1 Summary of Primary Strategies for Mitigating the Effects of Potential Impacting Near-Earth Objects

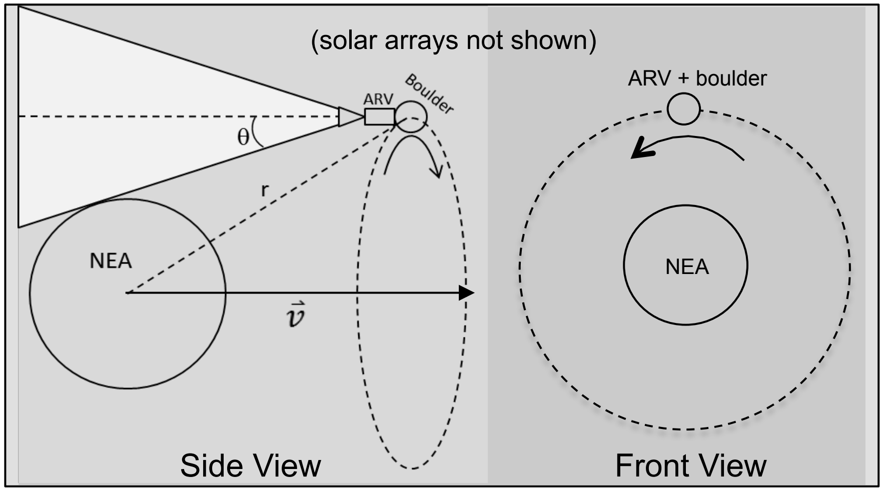
Strategy	Range of Primary Applicability
Civil defense (e.g., warning, shelter, and evacuation)	Smallest and largest threats. Threat of any size with very short warning time.
Slow push (e.g., "gravity tractor" with a rendezvous spacecraft)	A fraction (<10%) of medium-size threats. Usually requires decades of warning time.
Kinetic impact (e.g., interception by a massive spacecraft)	Most medium-size threats. Requires years to decades of warning time.
Nuclear detonation (e.g., close-proximity nuclear explosion)	Large threats and short-warning medium-size threats. Requires years to decades of warning time.

Enhanced gravity tractor approach using mass of retrieved boulder increases applicability

Planetary Defense Demonstration Options

Option 1 **Gravity Tractor**

Goal **Demonstration of Technique and Measurable Change in NEA Orbit**



Description:

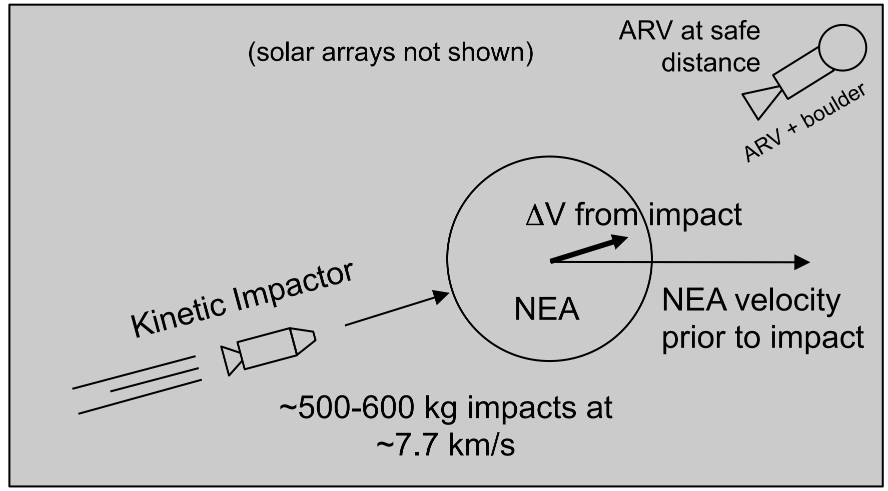
- ARV or ARV+boulder uses SEP thrusters to maintain distance from NEA.
- Gravitational attraction of ARV causes NEA orbit change.
- Spiral orbit of ARV avoids plume impingement on NEA.

Rationale:

- Excellent synergy with mission - boulder mass enhances method.
- Requires little to no modification of ARV - low cost option.

Option 2 **Kinetic Impactor**

Goal **Demonstration of Technique and Measurable Change in NEA Orbit**



Description:

- Kinetic impactor launched with the ARV as secondary.
- Kinetic impactor trajectory permits end-of-mission arrival after ARV has moved away from NEA.
- Significant change in the NEA orbit can be demonstrated.

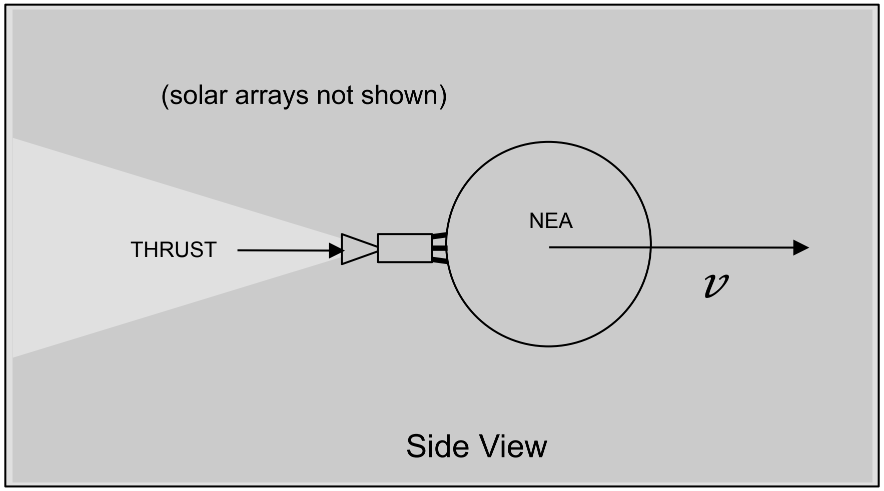
Rationale:

- Effective method for NEA orbit modification.
- High relative velocity allows for lower impactor mass.
- Relatively modest cost increase for the mission.
- Reduced cost by leveraging other proposed impactor missions.

Planetary Defense Demonstration Options

Option 3 **SEP Slow Push**

Goal **Demonstration of Technique Only**



Description:

- ARV interfaces/anchors to NEA.
- SEP cycles as NEA rotates, resulting in a net thrust in desired direction.
- Approach requires significant time to modify NEA's orbit.

Rationale:

- Excellent synergy with mission since ARV will likely contact surface during boulder collection. Understanding surface properties is likely critical for planetary defense.
- Requires little to no modification of ARV - low cost option.

Other Options Considered:

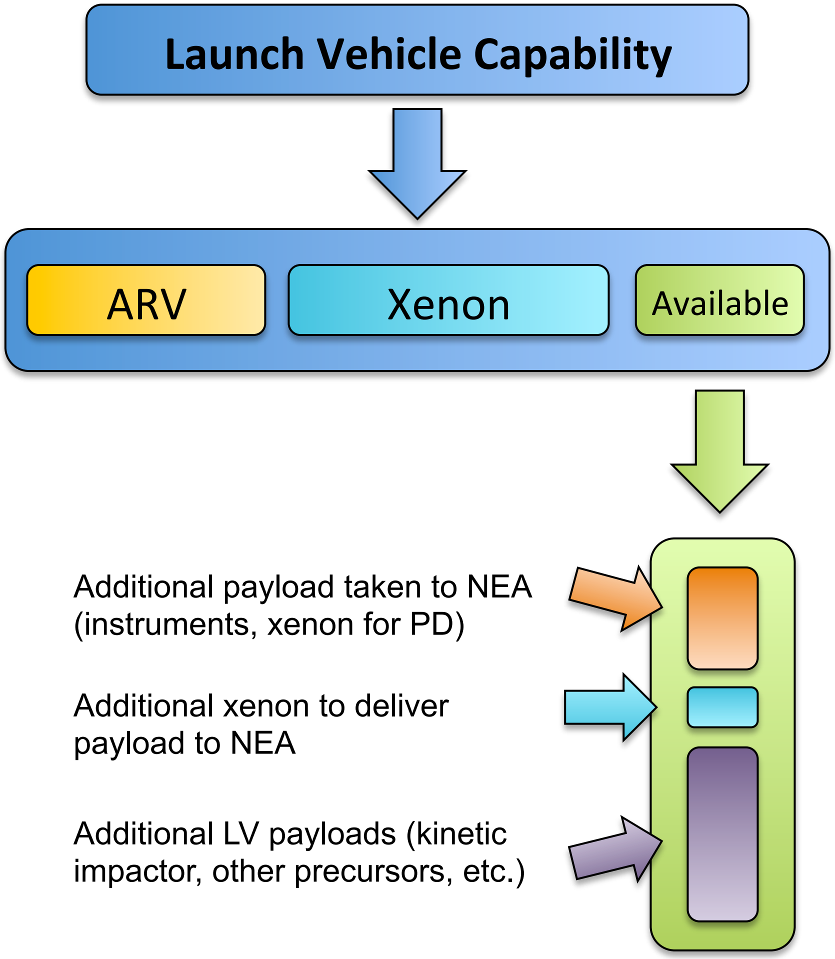
Evaluated based on relevance to ARM AATS mission as well as planetary defense in general:

KEY:
OM = orbit modification
TD = technology demonstration
F = fragmentation
FAR = further analysis recommended

Method/Demonstration	Goal	STATUS		Not Incorporated Due To:				
		Accepted	FAR	Cost	TRL	Complexity	Time Required	Risk
gravity tractor	OM	X						
slow push	TD	X						
kinetic impactor (deflection)	OM	X						
painting / coating to change orbit	OM						X	
painting / coating demonstration	TD						X	
solar sail	OM			X	X	X		
solar sail (EOM)	OM				X	X		
kinetic impactor (fragmentation)	F							X
kinetic impactor (EOM Deflection)	OM		X					
laser ablation	TD				X	X		
fast reaction kinetics	F							X
mass driver	OM			X	X	X		
stand-off nuclear blast	OM			X		X		X
surface/sub-surface nuclear blast	F			X		X		X
magnetic flux compression	OM			X	X	X	X	
multiple microprojectile bombardment	OM					X		
drilling /excavation	TD		X					
transponder / beacon	TD		X					
characterization	TD		X					
solar collector	TD			X	X	X		
mini-magnetospheric plasma propulsion	OM			X	X	X	X	
tether	TD					X		X
ion shephard	OM		X					

Mission Performance Trade-off

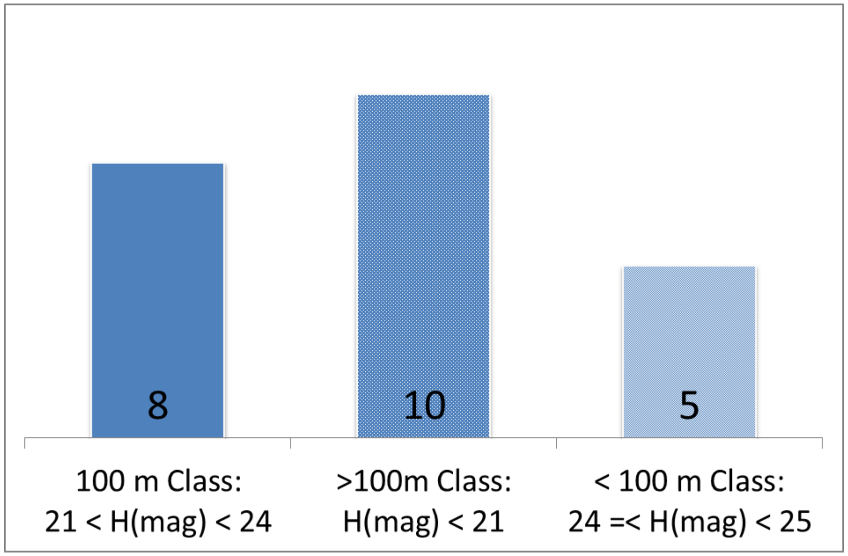
- Alternate approach for ARM allows flexibility by balancing:
  - Return mass
  - Time at NEA
  - Additional payload mass at NEA
  - Secondary Launch Vehicle (LV) payload mass
- Two cases:
  1.) Maximize boulder return mass
  2.) Trade xenon at launch vs. additional payload
- Two LVs assumed:
  1.) Falcon Heavy with 14.0 t delivered to Translunar Injection (TLI)
  2.) Atlas V 551 with 14.7 t delivered to 5,000 km apogee



Expanded Target Set

- **117** targets with return mass > 10 t
- **4** targets with past or future robotic mission with > 9 t return mass
  - Itokawa (1998 SF_{36}) (PHA)
  - Bennu (1999 RQ_{36}) (PHA)
  - 1999 JU_3 (PHA)
  - 2008 EV_5 (PHA) – mission still in selection process
- **8** targets in the 100 m class with radar observation opportunities before 2018 and with > 10 t return mass
  - 2002 NV_{16} (PHA)
  - 2006 CT
  - 2011 BT_{15} (PHA)
  - 1996 XB_{27}
  - 2007 EC
  - 2000 AC_6 (PHA)
  - 2010 VB_1
  - 2000 SJ_{344}

Targets with Radar Observation Opportunities and Return Mass > 10 t by Dec 2024



Falcon Heavy to TLI, ≥ 200 day stay

- **15** additional targets with radar observation before 2018 exist
- **12** additional targets with radar observation opportunities if return date is extended by one year to 2025 (100 m & > 100 m class)
- Return mass increases with later arrival date for many targets and new targets become available
- Observation of targets by space-based assets not yet studied (Spitzer or NEOWISE restart or archived data)

100 m Target Observation

NEA	H(mag)	Estimated Size(m)	Optical [Vp]	Arecibo [SNR]	Goldstone [SNR]
2002 NV_{16}	21.4	91-406	11/2013 ***[18.62]***	9/2013 ***[620]***	10/2013 ***[110]***
2006 CT	22.4	59-262	1/2014 ***[18.44]***	12/2013 ***[140]***	None
2011 BT_{15}	21.7	80-358	1/2014 ***[17.3]***	1/2014 ***[790]***	12/2016 [60]
1996 XB_{27}	21.7	80-360	10/2013 ***[18.2]***	5/2014 [15]	None
2007 EC	22.2	63-281	1/2015 ***[16.6]***	1/2015 ***[480]***	1/2015 [85]
2000 AC_6	21.2	123-229*	2/2015 ***[17.3]***	2/2015 ***[120]***	2/2015 [12]
2010 VB_1	23.3	38-170	6/2017 ***[17.7]***	6/2017 ***[2200]***	6/2017 [49]
2000 SJ_{344}	22.6	53-237	1/2018 ***[20.1]***	11/2017 [65]	None

***2000 AC_6 observed by NEOWISE**

< 100 m class & > 100 m class target information available in backup

Optical observation peak predicted visual magnitude [Vp]

Vp < 24 for detection

Vp < 21 -19 for light curves (rotation)

Vp < 19 - 17 for spectra

Radar observation signal-to-noise ratio [SNR]

SNR > 100 for shape

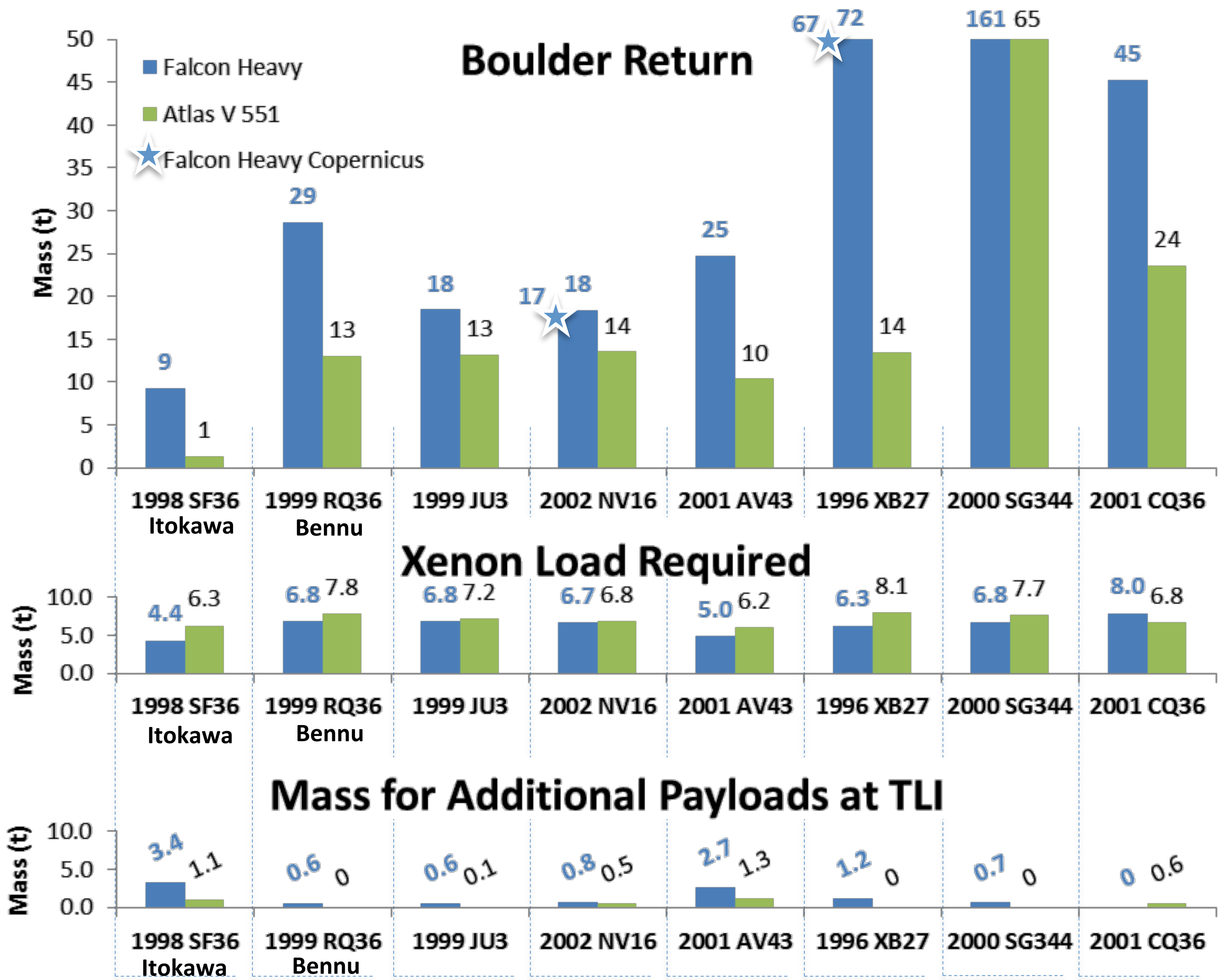
SNR > 1000 for surface features including boulders

Selected Targets for Mission Design

- Performance analysis for 3 targets with past or scheduled robotic observation
  - Itokawa (1998 SF_{36})
  - Bennu (1999 RQ_{36})
  - 1999 JU_3
- Performance analysis for 5 targets with good observability and/or high return mass
  - 2 with excellent ground-based observation opportunities – 2001 AV_{43} & 2002 NV_{16}
  - 1 with ground-based observation and large return mass – 1996 XB_{27}
  - 2 with no ground-based observation but large return mass – 2001 CQ_{36} & 2000 SG_{344}

Characterization Data	**Target Name**	**Itokawa**	**Bennu**						
	Target Designation	**1998 SF36**	**1999 RQ36**	**1999 JU3**	**2001 AV43**	**2002 NV16**	**1996 XB27**	**2000 SG344**	**2001 CQ36**
	Orbit Type	**Apollo**	**Apollo**	**Apollo**	**Apollo**	**Apollo**	**Amor**	**Aten**	**Aten**
	PHA		**PHA**	**PHA**		**PHA**			
	Absolute Magnitude [H(mag)]	**19.2**	**20.8**	**19.2**	**24.4**	**21.4**	**21.7**	**24.8**	**22.7**
	Estimated Size Range (m)	**535 x 294 x 209**	**580**	**840 - 970**	**23-105**	**91-406**	**72-97**	**19-86**	**56 - 79**
	Mean Density (g/cm2)	**1.95**							
	Estimated Mass (t)	**35800000**							
	Rotation Rate (rph)	**0.08**	**0.24**	**0.13**	**5.88**	**0.91**			
	Shape	**"Sea Otter"**	**Irr. Spheroid**	**Irr. Spheroid**					
	Type	**S(IV)**	**B**	**C**			**E?**		
	Boulders Detected	**Yes**	**Yes**						
Ground Based Observation	**Orbit Condition Code**	**0**	**0**	**0**	**3**	**0**	**0**	**2**	**0**
	Optical Observation				**Nov-13**	**Nov-13**	**Oct-13**		
	Magnitude (Vp)				***18.26***	***18.63***	***18.2***		
	Arecibo				**Nov-13**	**Sep-13**	**May-14**		
	SNR				***10000***	***620***	**15**		
	Goldstone				**Nov-13**	**Oct-13**			
	SNR				***2100***	***110***			

Mission Performance for Selected Targets



- Results from Mission Analysis Low-Thrust Optimization (MALTO)
- 200 day duration at target
- Maximum return mass assumed
- Atlas V 551 includes Earth spiral of additional payload

Operations at Target NEA

Characterization

- Flybys to characterize gravity field, total mass, and shape
- Surface characterization and boulder identification

Initial Orbit Determination (OD) and Gravity Tractor Demonstration

- Measure baseline NEA orbit
- Maneuver to spiral orbit
- Perform gravity tractor technique demonstration

Boulder Collection & Surface Operations

- Boulder collection rehearsal including practice descent
- Payload deployment
- SEP slow push planetary defense technique demonstration
- Boulder collection

Enhanced Gravity Tractor Demonstration and Orbit Determination (OD)

- Maneuver to spiral orbit
- Perform enhanced gravity tractor orbit modification demonstration utilizing retrieved boulder
- Measure change in NEA orbit

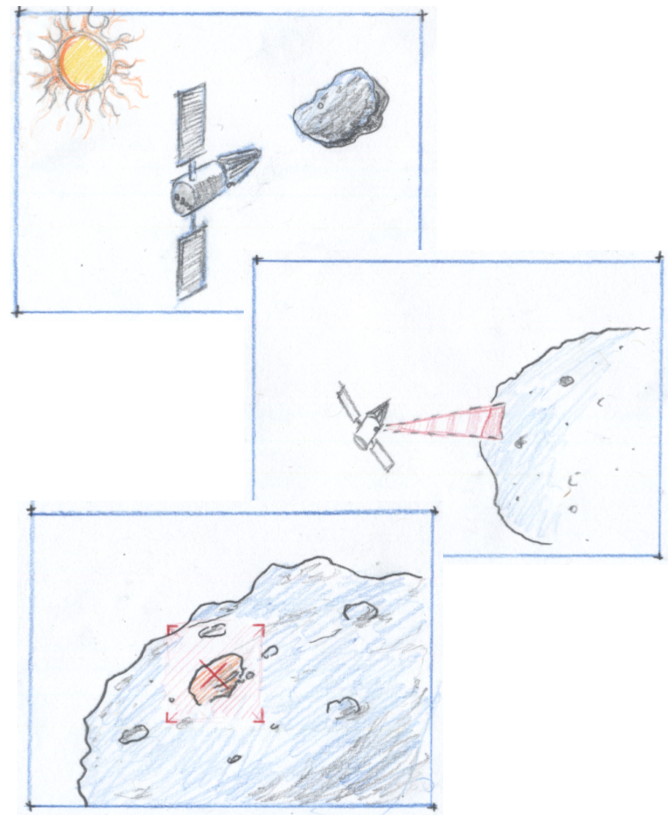
Kinetic Impactor Demonstration and Orbit Determination (OD)

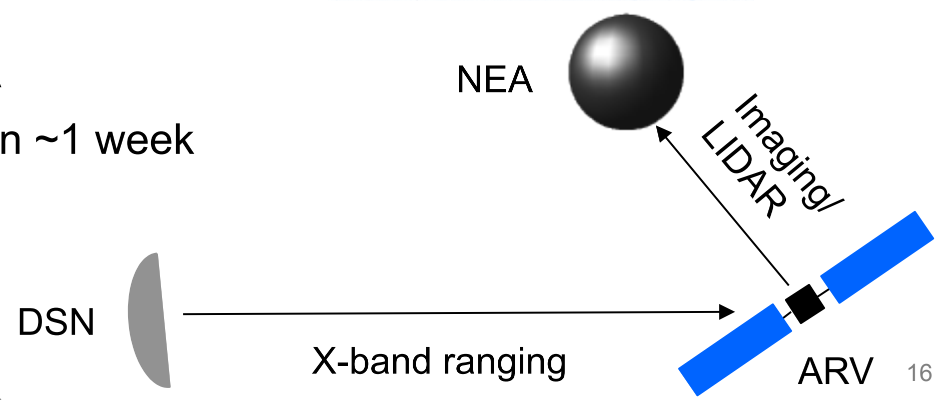
- Maneuver to safe distance
- Kinetic impactor orbit modification demonstration
- Measure change in NEA orbit

Notional 200 day timeline in backup

Rendezvous, Characterization, and Ranging

- During rendezvous: narrow-angle camera mapping
  - Refine shape model and spin measurement. Initial boulder detection.
- In the vicinity (~10 km)
  - Shape model refinement and boulder detection via narrow-angle camera and laser ranging
- Proximity (several asteroid radii)
  - Flybys to estimate NEA mass and inertia properties
  - Boulder characterization using thermal infrared spectrometer and possibly small hosted free-fliers
  - Ground penetrating radar to enable boulder characterization and gather surrounding surface context
- Asteroid trajectory estimation
  - Deep Space Network (DSN) to ARV to NEA
  - Can detect ~500 m ephemeris change within ~1 week





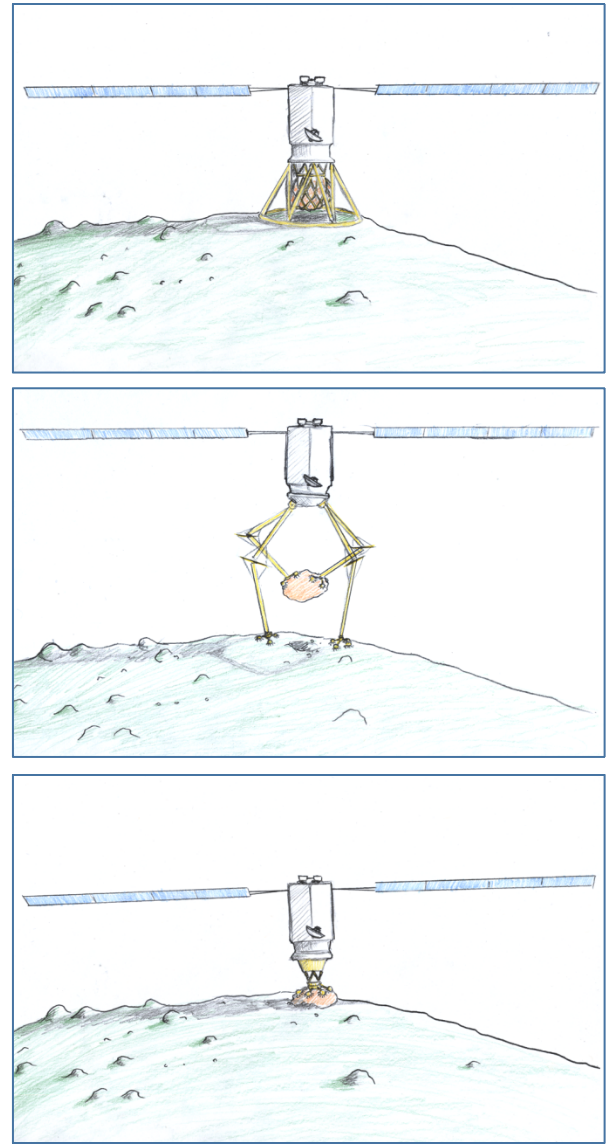
Surface Interaction Challenges & Possible Mitigation Approaches

- Proximity of large solar arrays to surface
  - Limit boulder retrieval to acceptable surface locations
  - Orient arrays away from surface during surface operations
  - Modify design to include a separable spacecraft for boulder collection

- Breaking weak cohesive bond of boulder with surface
  - Push off mechanically (requires reaction force with surface of target NEA)
  - Use supplemental technique (vibration, gaseous N_2, etc.)
  - Utilize Reaction Control System (RCS) thrusters (lateral shear)
  - Utilize target NEA dynamics and inertia of spacecraft

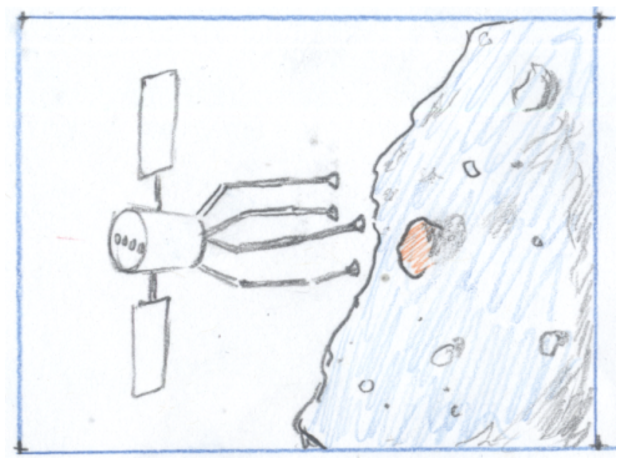
- Thruster plume impingement on surface while providing sufficient control authority for proximity maneuvers
  - Position RCS thrusters away from surface
  - Utilize coarse and vernier thruster configurations

- Environmental concerns in close proximity to surface (thermal, debris, electrical arcing, etc.) requires further study to determine if issues exist and potential mitigation approaches if necessary



Approach and Initial Contact

- Objectives
  - Safely approach target site
  - ARV capture system anchors to or maintains contact with surface
- Approach
  - Use RCS to approach and hover above the boulder site at a distance of 20 m above the keep-out sphere of radius of the maximum asteroid dimension
  - Descend at 0.1 m/s - To Be Refined (TBR)
  - RCS is required for descent
    - *Trade: Use capture system to dampen contact forces at surface*
- Initial Contact
  - Collection of contingency sample
  - Allows slow-push demonstration
    - *Trade: Initial contact directly on the boulder*
    - *Trade: Initial contact at a site removed from the target boulder (could be optimized for slow push or other demonstration)*
  - Grippers are actuated and tested for secure connection

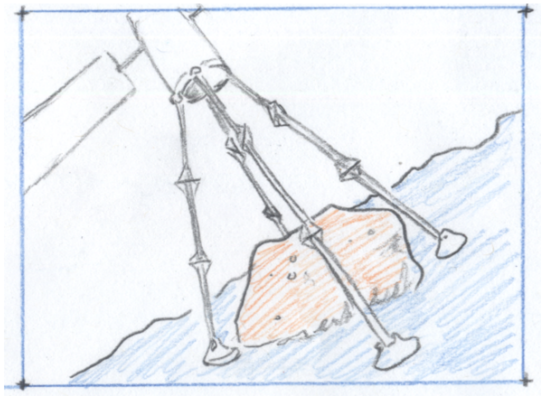


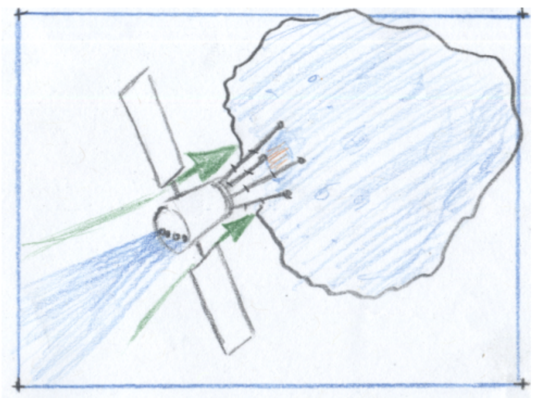
	NEA Rotation = 1 rph	
RCS design	spinner	tumbler
15.6 N / 22.2 N	3.1 kg	6.0 kg
200 N	2.4 kg	6.3 kg

Approach, hover, descent propellant estimates (100 m target NEA)

Pre Boulder-Collection Operations

- Objectives
  - Collect regolith samples and deploy additional payloads
  - Demonstrate slow push planetary defense technique with SEP thrusters
- Operations Description
  - Regolith samples collected
  - Deployment of additional payloads
  - SEP thrusters activated to test connection and surface stability
  - Surface integrity is monitored and thrusting is continued to demonstrate "slow push" planetary defense operations
    - Option to demonstrate thrust cycling and control required to impart a net ΔV in a single direction
    - Contingency: Immediate abort to a safe distance performed by capture mechanism (arms pushing) or other mechanical method
    - *Trade: Use thrusters for abort, but could disturb surface*
    - *Trade: Use extendible rod ("stinger") to push off of NEA*

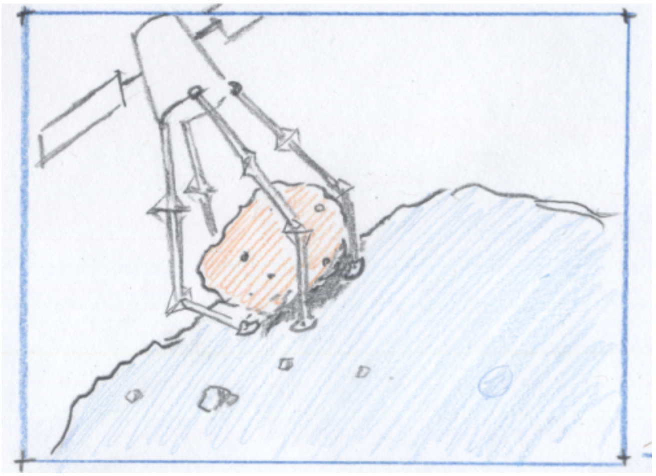




Boulder Collection Operations

- Objectives
  – Retrieve boulder with mass less than ARV capability

- Operations Description
  – *Assumptions*:
    - Final target area characterization, including sub-surface mapping utilizing ground penetrating radar, is complete
    - Target boulder is solid, coherent body
  – If the ARV has not been anchored to the boulder, the capture mechanism will be actuated to securely grip the boulder.
    - *Trade: Use of arms, net, cables, hybrid system, or direct grapple of the boulder via spacecraft with suitable gripper*
  – Capture mechanism adhesion to boulder is verified

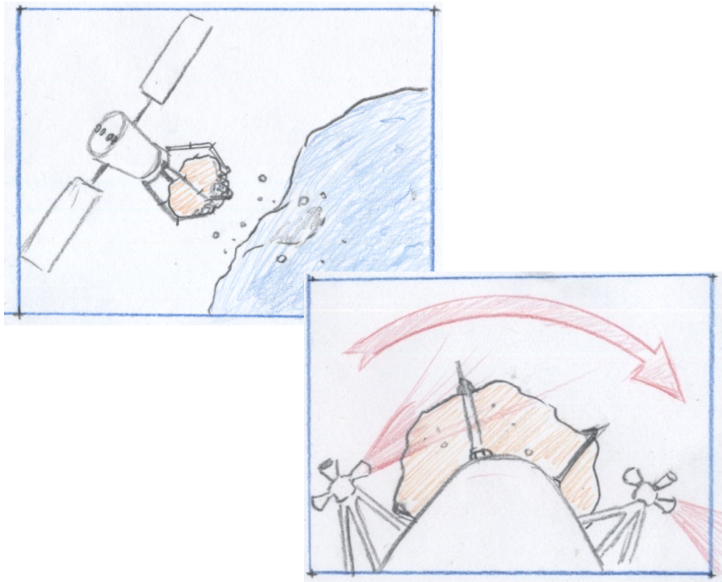


	NEA Rotation = 1 rph	
RCS design	spinner	tumbler
15.6 N / 22.2 N	70 tons	80 tons
200 N	196 tons	196 tons

Estimated limit of boulder mass for RCS capability (100 m target NEA)

Ascent and Transition to Gravity Tractor

- Objectives
  - Ascend from surface with target boulder and achieve stable attitude
  - Transition to gravity tractor demonstration
- Operations Description
  - Use capture mechanism to achieve initial separation
    - *<u>Trade:</u> If arms are used for capture, push off to achieve separation*
    - *<u>Trade:</u> Use extendible rod ("stinger") to push off of NEA*
  - Use RCS thrusters to ascend to 20 m and then drift to staging altitude
  - Perform despin of the boulder/ARV system
    - *<u>Contingency:</u> In the event that the ARV loses boulder, ARV moves to safe distance while avoiding any debris*
    - *An additional approach and boulder collection attempt can be conducted*
  - Use SEP and RCS thrusters to achieve initial attitude and position in preparation for gravity tractor demo



	NEA Rotation = 1 rph	
RCS design	spinner	tumbler
15.6 N / 22.2 N	9.2 + 0.6 kg (70 tons)	13+0.3 kg (80 tons)
200 N	20.8 + 1.8 kg (196 tons)	28.5+0.8 kg (196 tons)

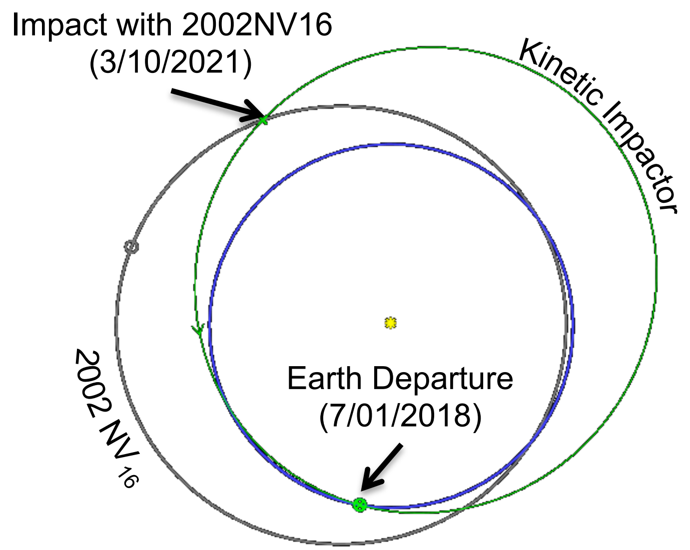
Estimate of RCS+SEP propellant mass for ascent and reorientation to initial attitude and position for gravity tractor demonstration (100 m target NEA)

Gravity Tractor Demonstration – Orbit Modification

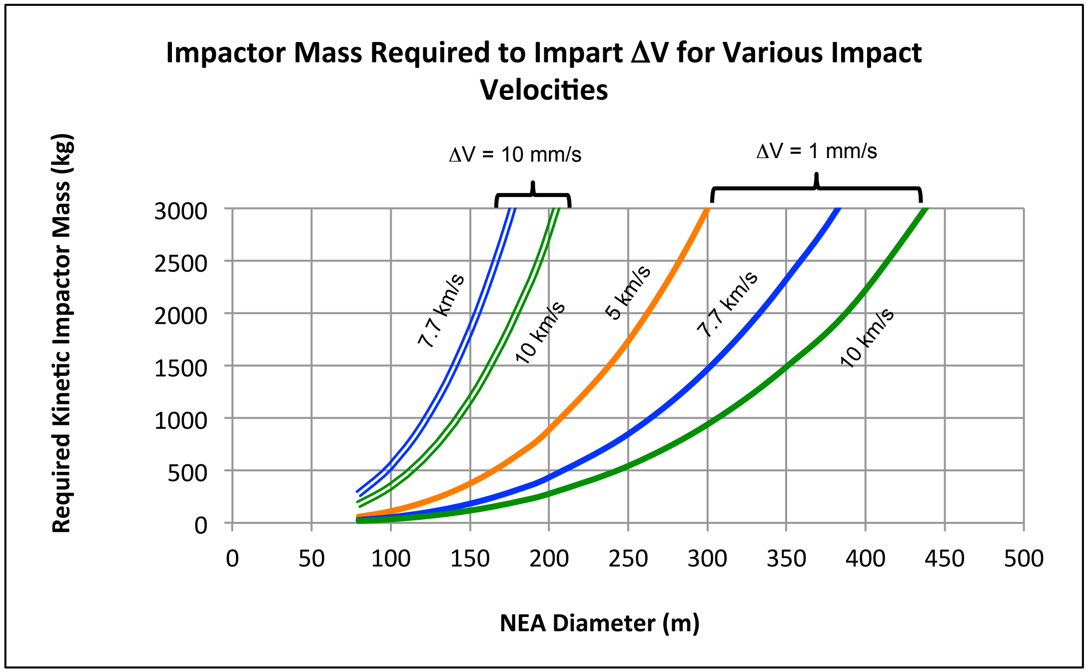
- Boulder mass greatly increases effectiveness
  - Deflection goal can be accomplished on a 250 m NEA with 3 m boulder in ~100 days
  - Even without a boulder, deflection goal can be met for 120 m or smaller NEA
- 300 – 400 kg of xenon propellant covers all feasible gravity tractor demonstrations based on the notional timeline
- Gravitational force exceeds ARV SEP thrust for 5 m boulder coupled with larger NEAs
  - Must move further away from NEA to balance gravitational force which reduces the benefit of larger boulder
  - Causes the bends in the 5 m boulder curves

Kinetic Impactor Demonstration – Orbit Modification

- Kinetic impactor spacecraft co-manifested with the ARV follows different trajectory and arrives near end of mission with ARV located at a safe observational distance. Utilizes chemical propulsive stage with a different lunar gravity assist than the ARV, along with a powered Earth flyby (1 km/s).
- High speed impact occurs within 20 degrees of the NEA velocity vector and causes measureable change in the NEA orbit.
- 2002 NV_{16} used as example case to verify feasibility of trajectory and estimate impact velocity.
- Mass at impact of 530 kg (estimate for ISIS mission concept) with nominal impact speed of 7.7 km/s can impart a ΔV of 1 mm/s on a ~220 m NEA assuming a conservative momentum amplification factor.



Kinetic Impactor completes two orbits around the sun before arriving at target.



Each line is for a constant impact velocity.

Performance Floor Payload Suite

Boulder retrieval		
Objective	**Instrument(s)**	**Necessary performance**
Long-range optical navigation	Narrow-field camera	Target detection. Single channel.
Mapping, including boulder detection	Narrow-field camera; laser range finder/LIDAR	Resolution < 0.1 m/pixel, preferably significantly better.
Boulder shape model	Narrow-field camera and/or LIDAR	Resolution < 1 cm/pixel
Proximity navigation	Wide-field camera and/or LIDAR	~ 1 cm / pixel
Assessing boulder binding to asteroid/boulder mass estimate	Cameras (e.g. signs of motion)	~ 10 cm / pixel

Planetary defense		
Objective	**Instrument(s)**	**Necessary performance**
Trajectory-change measurement	Spacecraft DSN ranging + optical and/or LIDAR ranging between spacecraft and asteroid + X-band transponder	Best feasible. Drives design of planetary defense demonstration.
Shape model	Narrow-field camera and/or LIDAR	
Gravity field characterization	DSN spacecraft ranging + X-band transponder	

Necessary instruments
Narrow-field camera
Wide-field camera
LIDAR or laser range finder
X-band transponder

Instrument suite similar to ARM reference approach

Reference approach
Narrow-field camera
Wide-field camera
LIDAR
Imaging spectrometer

Additional Payload Options

Boulder-selection focused measurements		
Observations	**Rationale**	**Instrument(s)**
Assessing boulder binding to asteroid/ boulder mass estimate	Boulder selection	Ground penetrating radar, thermal infrared spectrometer (boulder density estimation), small hosted free-fliers
Boulder-scale surface composition	Boulder selection, context, planetary defense, resources	Visible/infrared spectrometer (Point spectra okay, wavelength: 0.5 – 4 micron, spectral resolution >~ 100)

Planetary defense, science, and resource focused measurements		
Observations	**Rationale**	**Instrument(s)**
Regolith composition	Context, planetary defense, resources	Visible/IR spectrometer, regolith sample collection system
Interior structure	Context, planetary defense, resources	Ground-penetrating radar, gravity field characterization through DSN ranging
Near-surface composition and hydration state	Context, planetary defense, resources	Neutron spectrometer, gamma ray spectrometer
Multi-point/mapping contact and close-proximity characterization	Boulder selection, context, planetary defense, resources	Small hosted free-fliers and/or hoppers (e.g. CubeSats). Payloads could include Mössbauer and x-ray fluorescence spectrometers, seismometers, microscopes, neutron spectrometers, etc.
Mechanical properties	Planetary defense, resources	Projectiles, small hosted free-fliers carrying surface-interaction experiments

Boulder target selection upgrades
Ground penetrating radar
Thermal infrared spectrometer
Visible/IR spectrometer

Instruments and small hosted free-fliers may be selected competitively and/or provided by international collaborators.

Planetary defense, science, and resource upgrades
Regolith sample
Neutron spectrometer/gamma-ray spectrometer
Projectiles
Small, low-cost hosted free fliers, hoppers, etc.

Capture System Implications on Crew Operations (Returned Boulder)

- Objectives
  - Enable or enhance crew access and mobility/translation around the returned boulder during Extravehicular Activity (EVA)
  - Enable boulder interaction (tool operation, sample collection, payload deployment, etc.)
- Comparison of Potential Concepts

	Air-beams & bag (reference capture system)	Net with inflatable/deployable mechanism	Manipulators with end effectors/grippers	Grippers only
Pros	1. Prevents escape of loose material	1. Provides access to the majority of the boulder surface 2. Prevents large pieces from separating and creating debris near the ARV 3. Provides translation lines to EVA crew over entire boulder surface	1. Relatively short length provides open access to entire boulder surface 2. Can be used for EVA crew positioning or payload manipulation 3. History of operations	1. Provides open access to entire boulder surface
Cons	1. Encloses boulder reducing direct access 2. Enclosed space, loose fabric, and tension lines add obstacles to EVA Crew mobility 3. Restricts deployment of large payloads on the surface 4. Complex inflatable strut, joint, and bag design (nonlinear, difficult to simulate)	1. Does not contain loose debris 2. Restricts deployment of large payloads on the surface	1. Does not contain any loose debris	1. Does not contain any loose debris

Benefits of Alternate Approach (1 of 2)

Area	Key Benefits
Discovery and remote characterization	• Discovery of large NEAs is much easier than < 10 m NEAs • Large NEAs can be observed at greater range with more accurate OD • Characterization opportunities for large NEAs are typically much longer in duration, have the benefit from advanced planning, and provide more detailed measurements, including composition • Spectroscopic and/or radar observations are easier, are typically much longer in duration, and can be scheduled in advance (almost all NEAs with known spectral types are large) • Remote confirmation of the presence of boulders vs. confirmation of acceptable size/mass of <10 m NEA
Planetary defense	• PD demonstrations can performed on a large NEAs that are of size that is a threat to Earth • Provides applicable operational experience that is not obtained by capturing a < 10 m NEA
Material collection and return	• All NEAs that have been visited have discrete rocks ranging from gravel to large boulders • Ability to select size/mass of returned material from a slowly rotating NEA provides mission flexibility and robustness • Coherent/monolithic boulder vs. <10 m NEA which may be a “rubble pile”

Benefits of Alternate Approach (2 of 2)

Area	Key Benefit
Technology and extensibility for future missions	• Capture system options provide more extensible to other missions (manipulators, grippers, nets, end-effectors, etc.) • Operations near the surface of a large NEA are more applicable to future human missions to small planetary bodies (NEAs and Martian moons) than small, potentially rapidly rotating NEAs • Better understanding of mechanical and morphological properties of class of NEAs that will visited by humans and robots
Science	• Much higher likelihood of finding a water-rich, carbonaceous NEA • Greater diversity (characterization and sample) • Visiting a larger NEA and maintaining the integrity and geological context of the returned material to the greatest extent possible has increased interest across the Agency
Space-based resources	• Much higher likelihood of finding a water-rich, carbonaceous NEA • Possibility of water-rich, carbonaceous boulders on another NEA type (Itokawa’s “black” boulders)
Crew interaction	• No impediment from bag(s) for crew access of NEA material and unintended release of material • Capture system can facilitate crew during EVA, by either positioning them, provide traverse lines, or providing tool accessibility

Areas for Additional Analysis

- Additional trajectory analysis and optimization
- Refine mission operations timeline
  - Instrument operations and requirements
  - Maneuvers and proximity operations requirements
  - Orbit determination approach and requirements
- Perform high-fidelity 6-Degree of Freedom (DOF) simulations to examine boulder collection dynamics, proximity operations, and planetary defense demonstrations
  - Simulate range of target NEA parameter and boulder locations
  - Analyze impact of target NEA spin state, surface operations, and boulder retrieval location on power generation/shadowing, thermal loads, and communications
  - Perform dynamic analysis of applying reaction force with various models of soil integrity for breaking weak cohesive bond of boulder with surface
  - Investigate RCS thruster plume impingement on surface
  - Determine capture system loads during all mission phases
  - Analyze systems for gripping the captured boulder (microspines or others)

Explore sensitivities, prepare simulation, and design trajectories in preparation for improved target characterization

Summary (1 of 2)

- Candidate NEAs have been identified from the list of known near-Earth objects that provide significant return mass (~10-160 t using Falcon Heavy launch vehicle with a 200 day stay).
- Itokawa (1998 SF_{36}) is characterized (gravity, mass properties, boulder distribution, etc.) and ~9 t can be returned
- Alternate approach provides significantly more candidate NEAs for a return in the 2025 timeframe
  - There are several known targets we will observe from Earth with radar later this year and early next year
  - Multiple, well-characterized targets with extended launch/departure windows are critical for mission flexibility
- Variable boulder size allows for flexibility and enables valuable operations

Summary (2 of 2)

- Time at NEA and delivered payload mass can enable:
  - Thorough target characterization
  - Planetary defense experiments and demonstrations
  - Scientific exploration
  - Retirement of Strategic Knowledge Gaps (SKGs) for future human exploration
  - In-situ resource utilization (ISRU) demonstrations
- Multiple capabilities/technologies exist and/or are in development for NEA interaction, boulder collection, and crew exploration
  - Manipulator arms, grippers, anchoring devices, traverse lines, nets, etc.
  - Options for the collection of samples from multiple locations can be incorporated

Closing Comments

- The driving requirement for ARM return mass needs to be carefully considered
  - Lots of mass of unknown composition may be of questionable value
  - The application of SEP as a future in-space "tug" to deliver 25-50 t class payloads (deep space habitat, landers, etc.) may be the most credible rationale for determining return mass
  - End-of-mission disposal options become more limited as mass increases
- No showstoppers have been currently identified with the technical aspects of going to a ~100 m class NEA and retrieving a boulder
- Alternate approach provides:
  - Incremental success at each phase of the mission and will accomplish foundational planetary defense and small body science
  - Relevant demonstration of planetary defense techniques that provides an exciting mission that can garner additional support